

## MEASUREMENT OF RESIDUAL STRESS USING MAGNETIC BARKHAUSEN NOISE ANALYSIS

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In this presentation we very briefly review the concepts involved in stress measurement by means of the Barkhausen effect, and cite the major instances of its practical application; the major part of the paper is devoted to a presentation of some recently obtained results regarding the effects of plastic deformation, and of biaxial stress fields.

The Barkhausen Noise Analysis approach to determining residual stress in ferromagnetic materials is based upon the well known fact that the magnetization changes in abrupt, irreversible increments called Barkhausen jumps. This is illustrated in Fig. 1 which shows what a portion of a typical hysteresis loop would look like with suitably sensitive detection methods. Barkhausen jumps occur mainly in the steep part of the hysteresis loop and are primarily associated with movements of  $180^\circ$  domain walls. The rapid changes in magnetic flux accompanying Barkhausen jumps are capable of inducing voltage pulses in a detection coil inductively coupled to the specimen, as shown in the oscilloscope photograph in Fig. 2. These pulses are found to be somewhat random in amplitude, duration, and temporal separation, and can roughly be described as "noise"; hence the term Barkhausen noise.

Several alternative methods exist for detecting and studying Barkhausen noise phenomena. The inductive method can be approached from either an analog or digital standpoint. It is the analog approach which the practical instrumentation developed to date has utilized. A block diagram is shown in Fig. 3. A C-shaped magnet is used to produce a time-varying magnetic field in the surface of the specimen and a small coil placed in proximity to the specimen surface is used to detect the Barkhausen noise voltage. Filtering is used to select the desired frequency range of interest, generally from 1 kHz to 10 kHz or higher. An analog signal is obtained by detecting the envelope of the burst of Barkhausen pulses resulting from a single reversal of the specimen magnetization. This signal can be displayed or its peak value read out on a meter; an example is shown in Fig. 4. A photograph of a practical stress measuring instrument is shown in Fig. 5.

Another approach to analyzing Barkhausen noise is to use a multi-channel pulse height analyzer to sort and count the individual Barkhausen pulses. Figure 6 shows a typical pulse height distribution resulting from a single reversal of magnetization for a silicon-iron specimen.

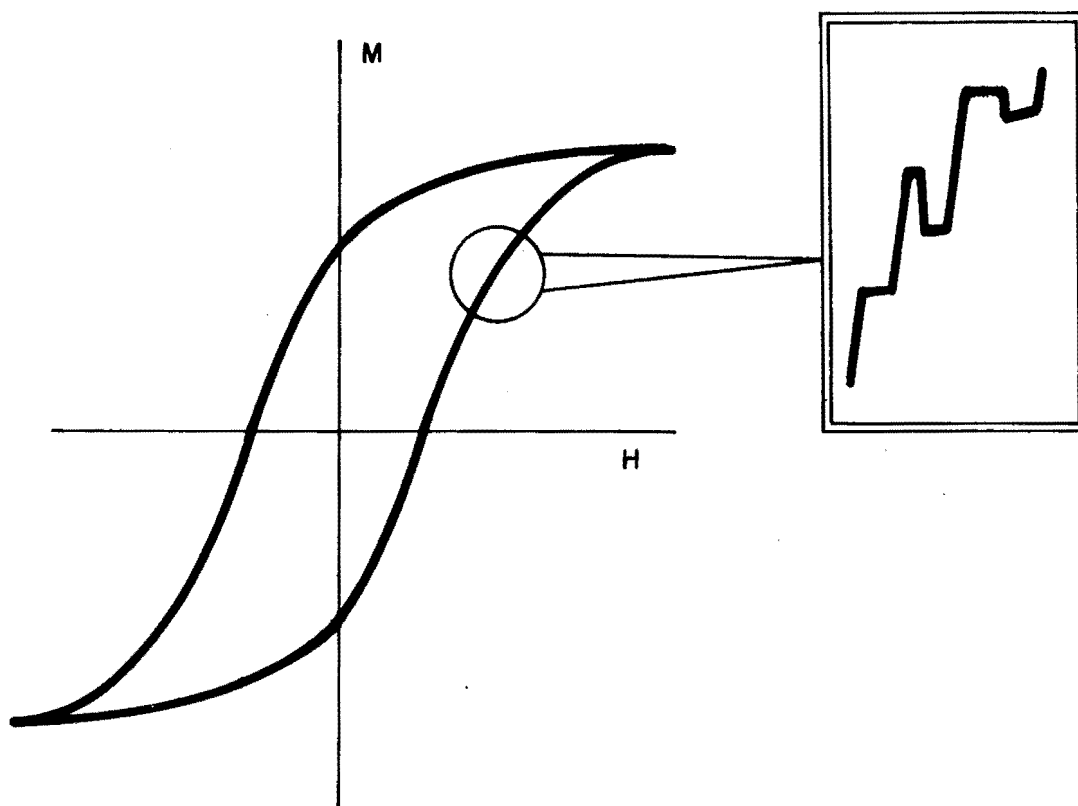
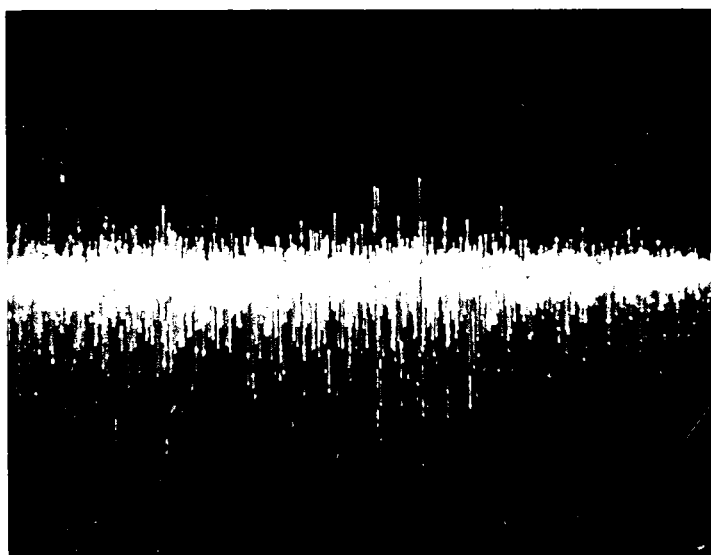


Fig. 1. Magnetic Hysteresis Loop and Barkhausen Jumps



10 mv/cm vertical sensitivity  
1 msec/cm sweep rate (horizontal)

Fig. 2. Barkhausen Noise Pulses

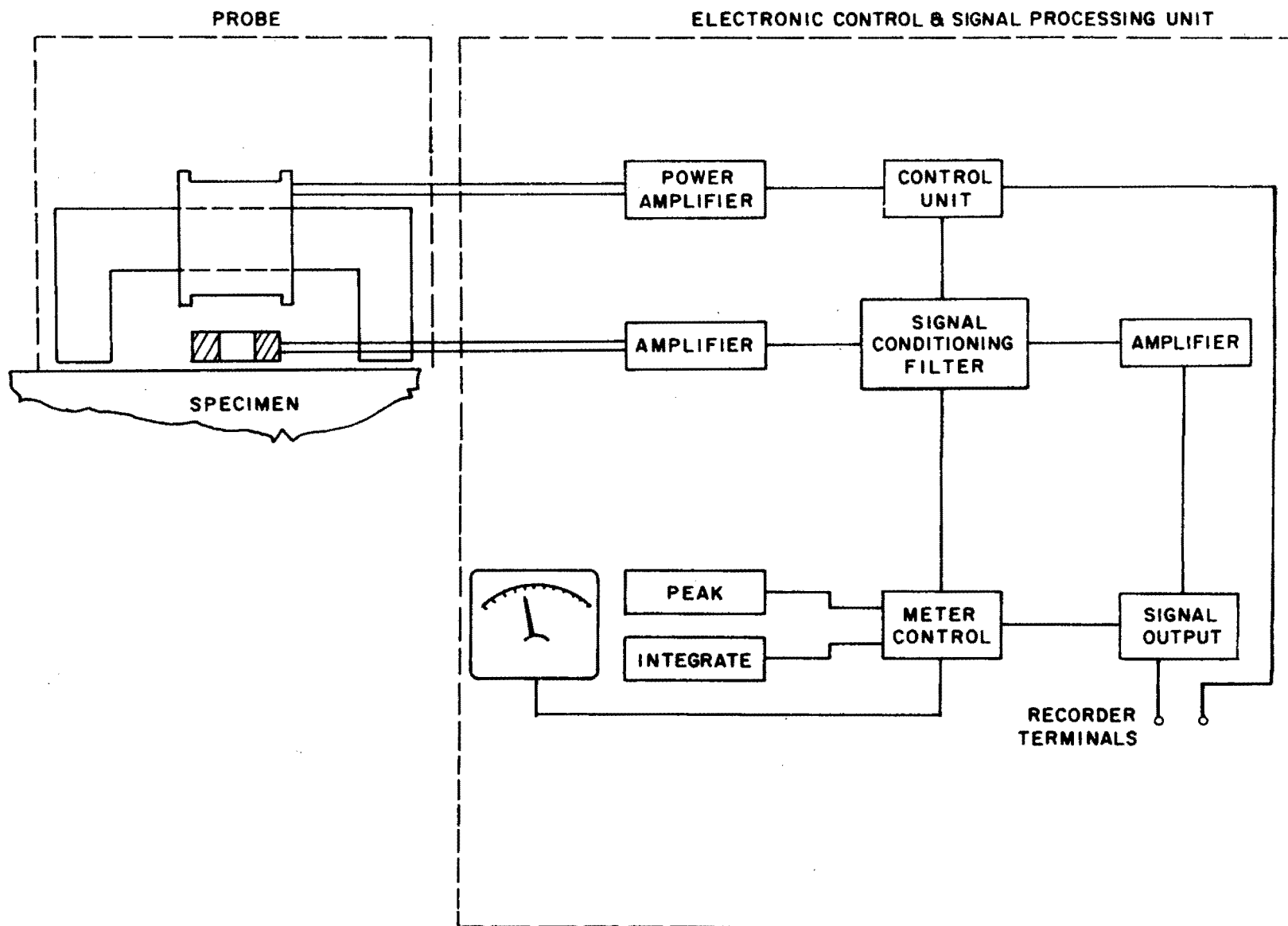


Fig. 3. Block Diagram of Measurement System

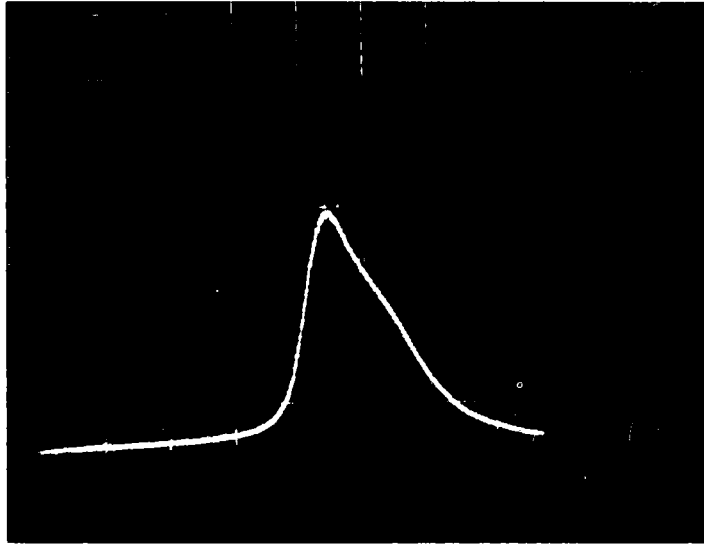


Fig. 4. Typical Analog Barkhausen Signal from AISI 4340 Steel

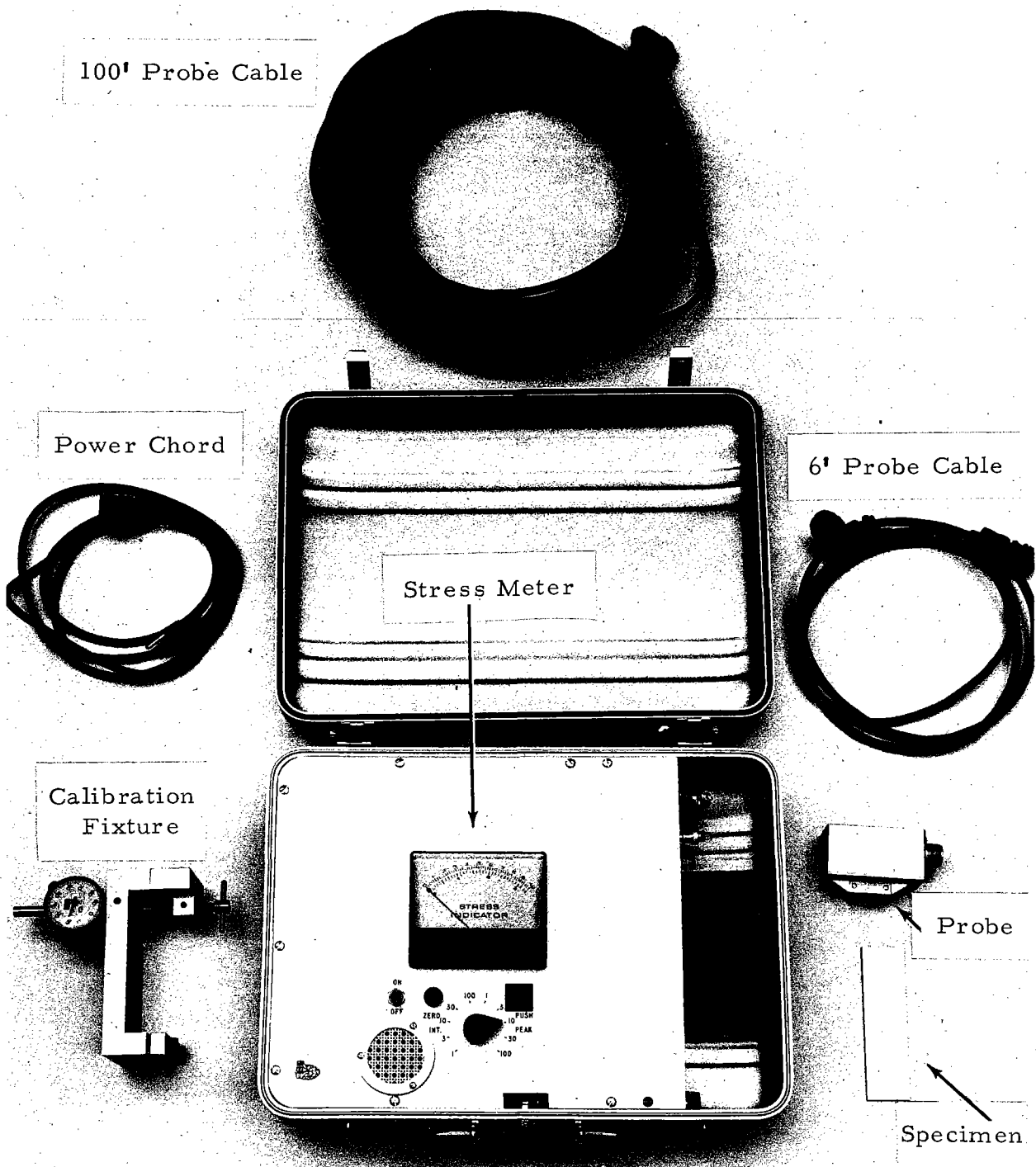


Fig. 5. Barkhausen Stress Measuring Instrument

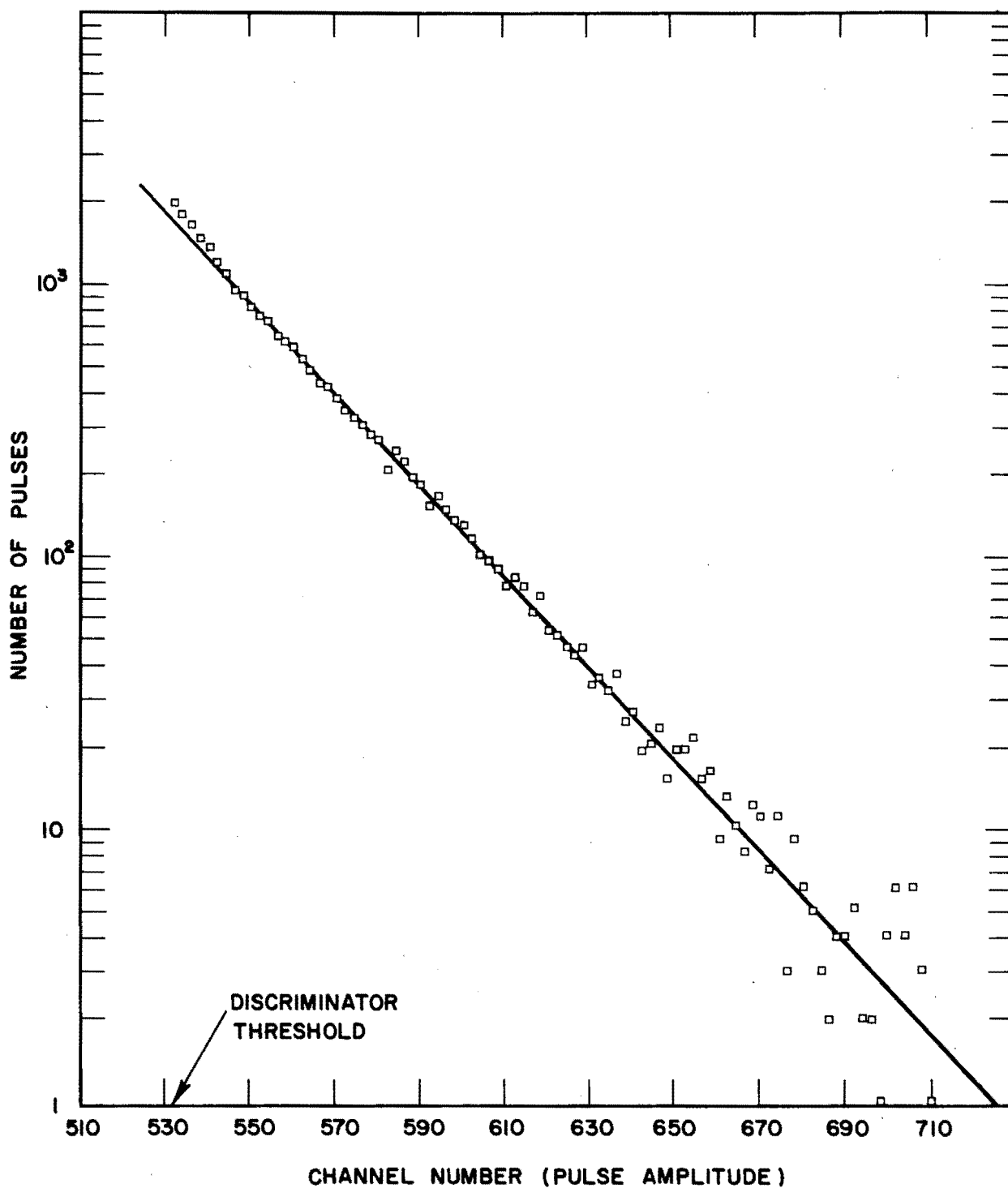


Fig. 6. Barkhausen Pulse Height Distribution for Annealed Polycrystalline Fe-3.2% Si Specimen

The dynamics of domain rearrangements can be directly investigated by imaging the surface domain structure of a specimen utilizing the Kerr magneto-optic effect. Figure 7 shows some results obtained in applying this approach to a large single crystal of silicon iron, for several states of magnetization. Domain rearrangements can be studied dynamically by means of high speed cinematography or photoelectric detection of intensity variations in the reflected light beam.

Use of the Barkhausen effect for measuring stress is based on the fact that the size, shape, and arrangement of the domains in a bulk ferromagnetic material, and thus the detailed domain dynamics are strongly influenced by the state of mechanical stress among other influential factors. Generally speaking, elastic tensile stresses give rise to high amplitude analog signals while elastic compressive stresses give rise to low amplitude signals. This is illustrated in Fig. 8 which shows a graph of the Barkhausen noise signal amplitude versus strain for cantilever bending. Similar results are obtained for specimens subjected to uniaxial stress. The signal amplitude is found to saturate at relatively low stress amplitudes, somewhat below the yield strength. In this range there is no significant change in defect structure, and the initial slope of the curve reflects a magneto-elastic interaction only.

Several practical applications based on a measurement of relative changes in stress state caused by known service histories have been developed. These include residual stress measurements in helicopter rotor blade spars, autofrettaged gun tubes, gas turbine engine components and rolling element antifriction bearing components.

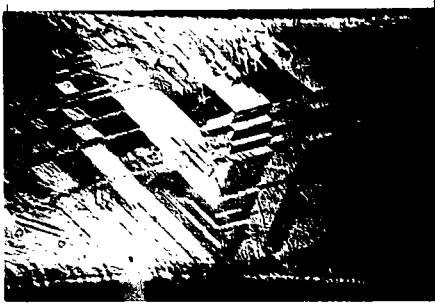
In addition to a macroscopic magneto-elastic effect, the Barkhausen noise signal is also affected by the interaction between domain walls and the internal microscopic defect structure. This has significance in measuring residual stress, which may be completely elastic, but is the result of a prior plastic strain history and therefore, an altered defect structure.

To investigate these latter points, some experiments were performed on specimens subjected to both elastic and plastic uniaxial deformation. In addition, experiments were performed on biaxial specimens to investigate the dependence of the Barkhausen signals on the relative orientation of the magnetization vector and the principal stress directions.

AISI 4130 alloy steel was chosen as the test material. It was obtained in the form of 1/8-inch thick hot-rolled plate in the normalized state. In this state, the steel is relatively ductile and moderately strong with a 0.2% offset yield strength of 79 ksi.

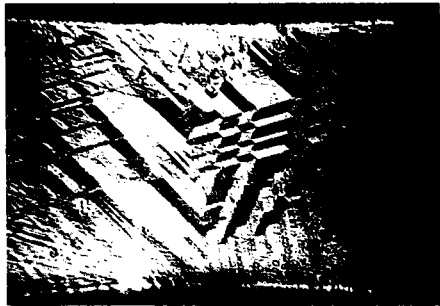
Two types of specimens were fabricated as shown in Fig. 9, simple uniaxial specimens for monotonic loading and cruciform specimens for biaxial loading; the rolling direction relative to the specimen geometry is indicated in Fig. 9. All specimens were appropriately strain-gaged to permit correlation



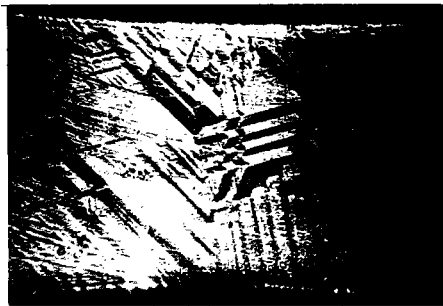


APPLIED FIELD:

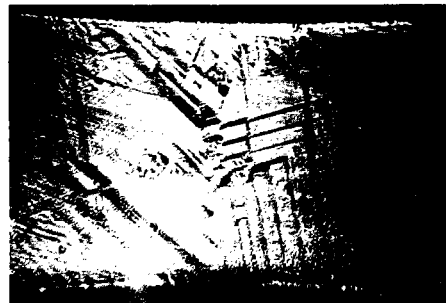
0 Oersteds



3 Oersteds



6 Oersteds



9 Oersteds



12 Oersteds

Fig. 7. Magnetic Domains on the surface of a Fe-3.1% Si Single Crystal

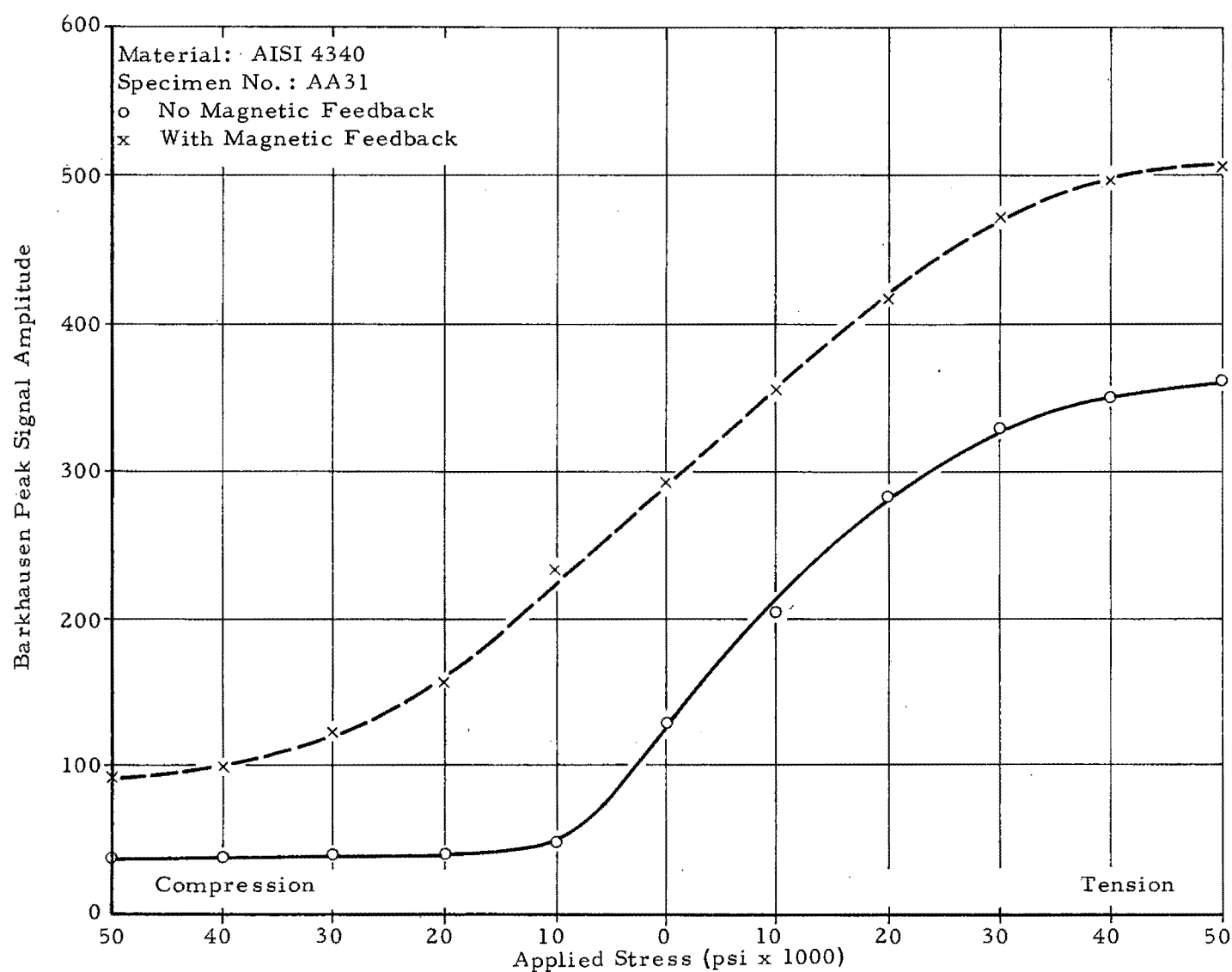
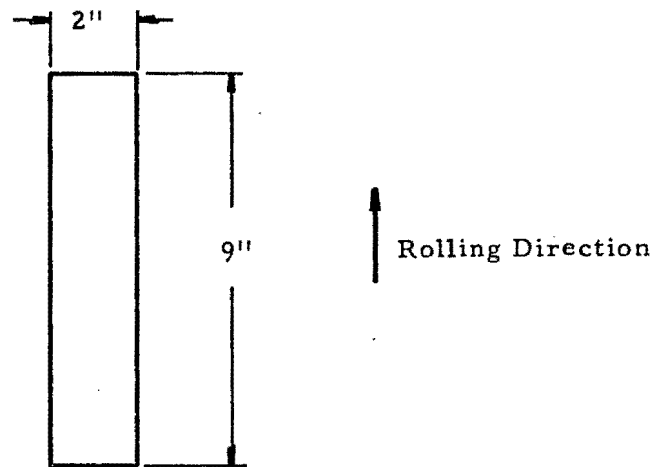
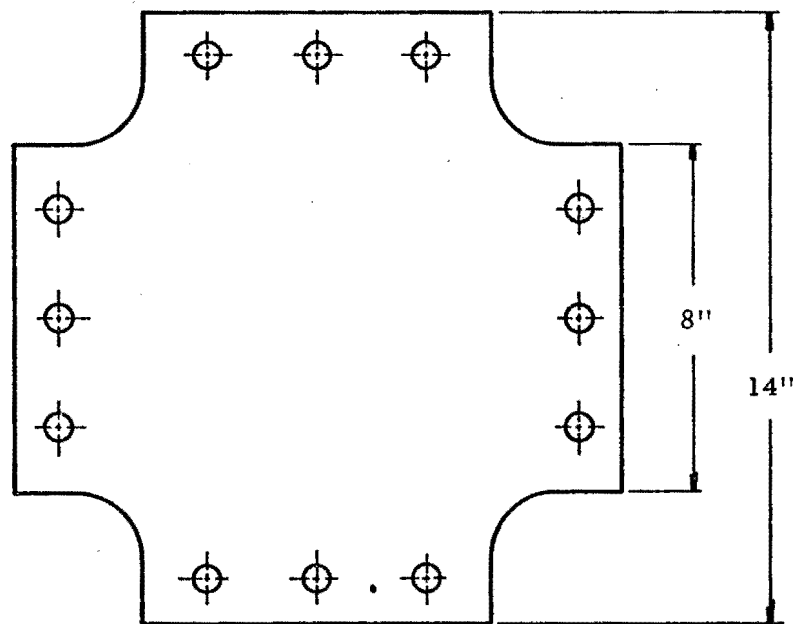


Fig. 8. Barkhausen Peak Readings versus Applied Cantilever Bending Stress for AISI 4340 Steel



(a) Uniaxial Specimen



(b) Biaxial Specimen

Fig. 9. Specimen Configuration for Uniaxial and Biaxial Experiments

of Barkhausen noise with strain; local stresses were calculated from applied loads. The inductive analog Barkhausen method was used for obtaining Barkhausen noise signals.

A uniaxially stressed specimen of normalized 4130 steel behaves mechanically as indicated by the solid lines in Fig. 10. The initial portion of the stress-strain curve is elastic up to a microyield stress ( $\sigma_{\mu y}$ ). Above  $\sigma_{\mu y}$  the curve is slightly nonlinear until just below the stress corresponding to the conventional 0.2% yield point, at which point gross plastic flow occurs.

Barkhausen readings were taken at fixed strain increments during both loading and unloading up to plastic strains on the order of 5%. Within the elastic limit, the Barkhausen readings were independent of whether the stress level corresponded to a load or unload sequence at a given plastic prestrain. Curves of constant Barkhausen readings are shown by dashed curves in Fig. 10. The Barkhausen signal amplitude readings at a given stress are normalized by dividing by the signal amplitude at zero stress prior to initial loading. Except as noted later in the discussion of the biaxial results, the applied stress  $\sigma_L$  is always longitudinal, which is also the rolling direction of the original plate.

The dependence of the normalized longitudinal Barkhausen peak signal amplitude  $\bar{B}^P_L$  upon stress level for three different plastic prestrains is shown in Fig. 11. Starting from the normalized state of the specimen, it is interesting to observe the rather dramatic effect which even a small plastic prestrain has upon the Barkhausen amplitude. In particular, the longitudinal peak signal at zero applied stress decreases by nearly an order of magnitude within the first two prestrain increments totaling 0.4% plastic strain. Thereafter, the zero-stress readings quickly drop to a very small value, remaining relatively constant with further plastic flow. It is obvious that the shape of the  $\bar{B}^P_L$  versus  $\sigma_L$  curve is very sensitive to cold work for  $\epsilon^P_L < 2.5\%$ . Regardless of plastic prestrain, however, the longitudinal Barkhausen signal increases with stress level until a value of 1.33 is attained; further increase in stress causes essentially no change in  $\bar{B}^P_L$ , until macroscopic plastic flow is reached. At this point,  $\bar{B}^P_L$  drops slightly to a value of approximately 1.25, remaining essentially constant with increasing plastic strain.

If the magnetizing and pickup coil are reoriented  $90^\circ$  so they are transverse to the specimen axis, the dependence of the "transverse" Barkhausen peak signal amplitude  $\bar{B}^P_T$  upon stress level is obtained as shown in Fig. 12. Here we see that within the same 0.4% strain increment in which  $\bar{B}^P_L$  dropped, for  $\sigma = 0$ , from 1.0 to 0.1, the transverse Barkhausen amplitude,  $\bar{B}^P_T$ , increases by 50 percent.  $\bar{B}^P_T$  also saturates at a stress level corresponding to that at which  $\bar{B}^P_L$  reaches its maximum, but in this case the saturation stress level corresponds to a minimum in  $\bar{B}^P_T$ . The

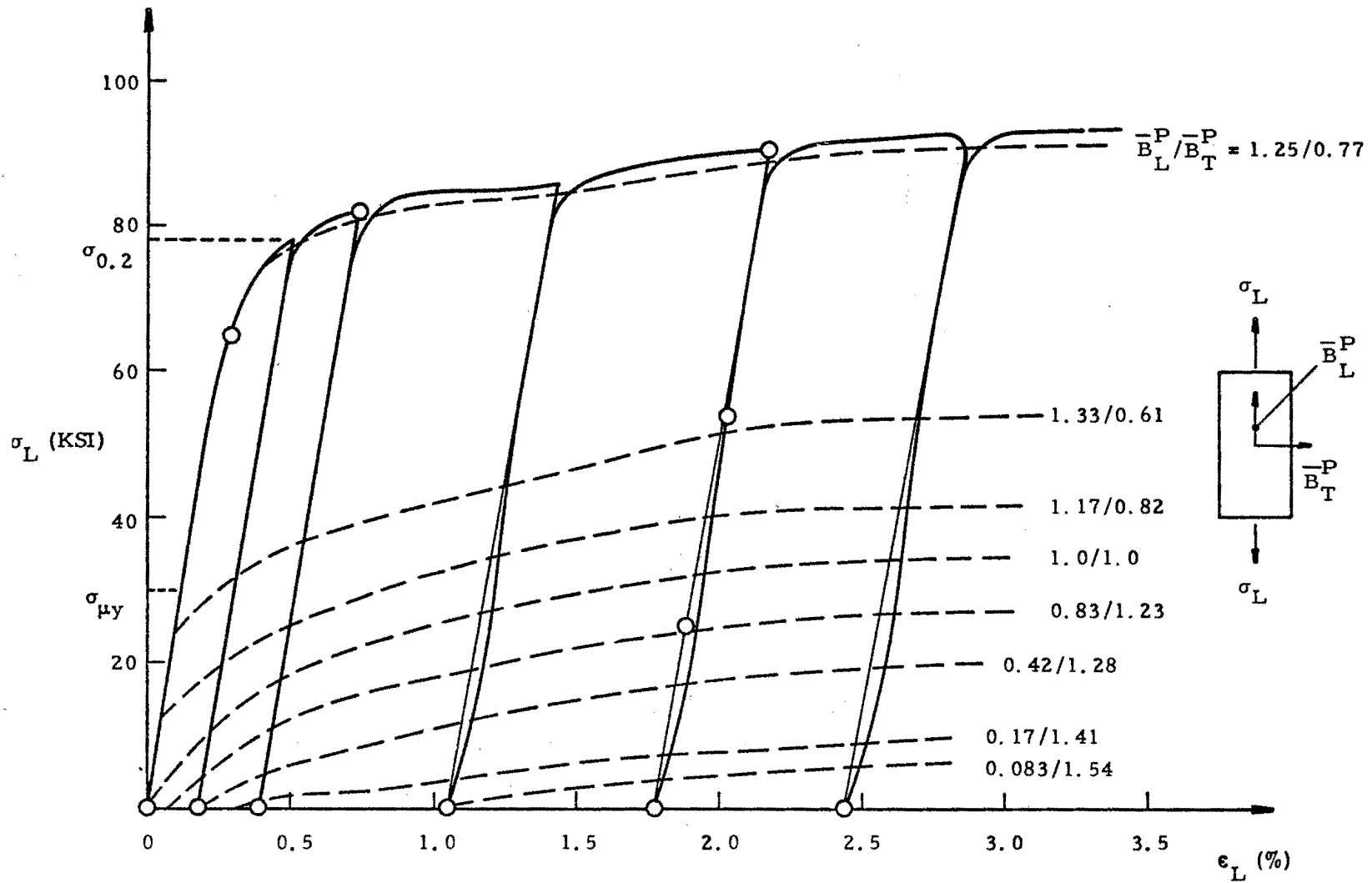


Fig. 10. Stress-Strain Behavior (Solid Lines) and Barkhausen Readings (Dashed Curves) for Normalized AISI 4130 Steel

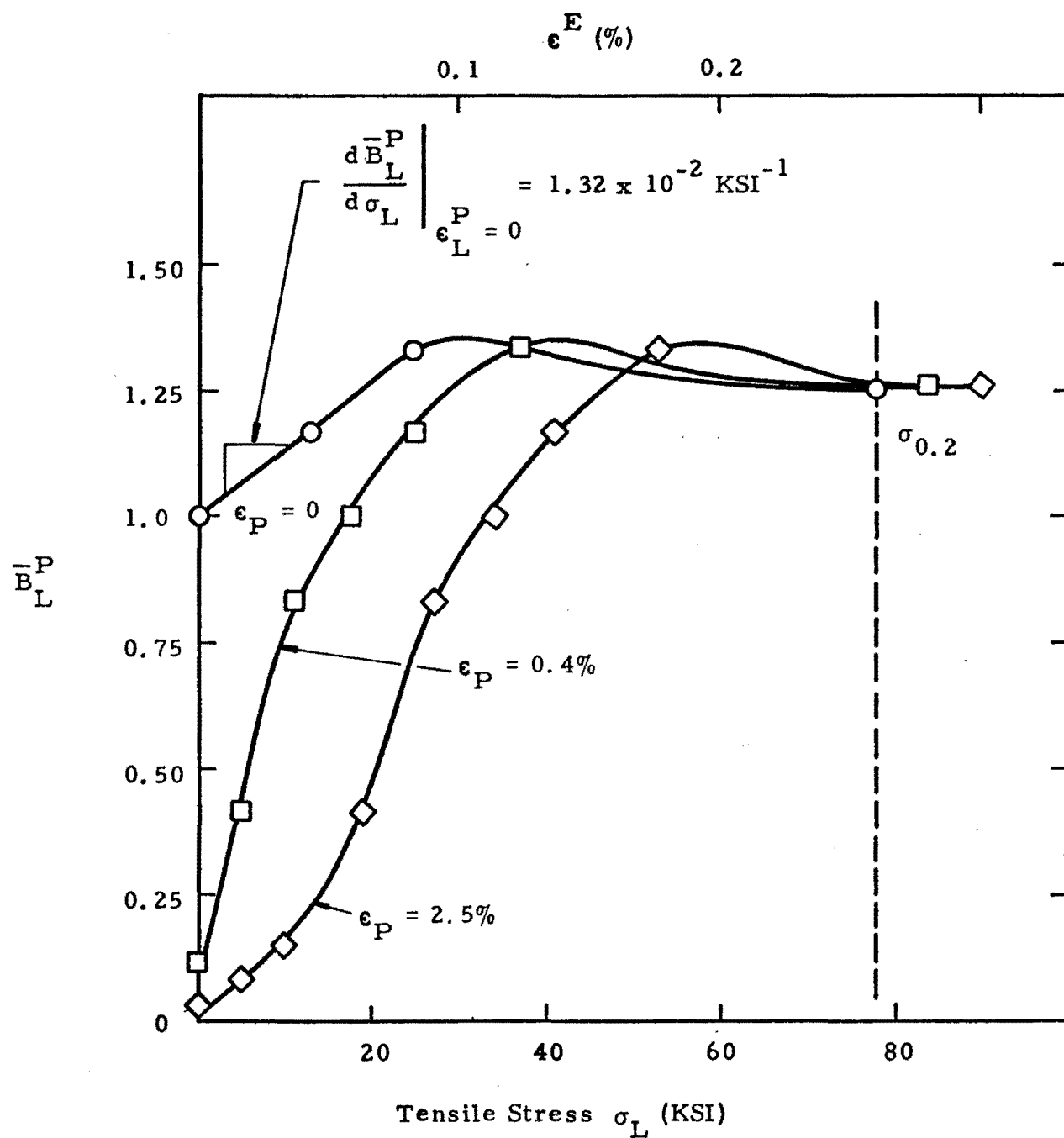


Fig. 11. Longitudinal Barkhausen Signal Versus Longitudinal Tensile Stress

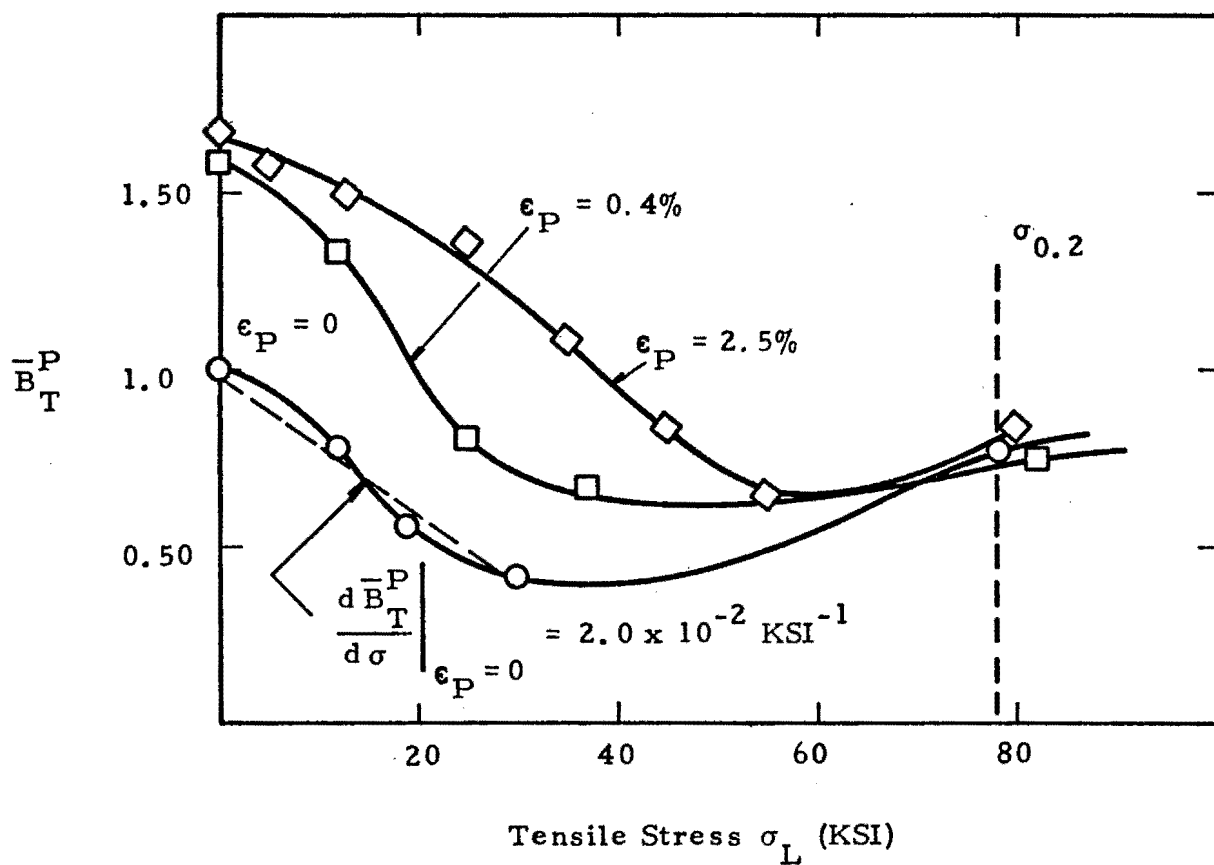


Fig. 12. Transverse Barkhausen Signal Versus Longitudinal Tensile Stress as a Function of Plastic Prestrain

results in Fig. 12 show the form of  $\bar{B}^P_T$  versus  $\sigma_L$  for the same three residual plastic strain amplitudes considered in the previous Figure for  $\bar{B}^P_L$ . The inverse relationship between  $\bar{B}^P_L$  and  $\bar{B}^P_T$  is evident upon comparing these two figures.

These foregoing results accord with previously obtained results: tensile elastic strain causes the Barkhausen peak signal to increase, while compressive elastic strain suppresses the noise amplitude<sup>1</sup>. This behavior is consistent with the domain model for materials of positive magnetostriction, such as 4130 steel; tension applied progressively to a unmagnetized specimen tends to align domain magnetization along the axis of tension until a dominant arrangement of  $180^\circ$  domains is obtained. This "critical" stress presumably corresponds to the observed uniaxial tensile stress above which the Barkhausen response is no longer affected by increasing stress; that is, higher stresses do not noticeably increase the existing preponderance of  $180^\circ$  domain walls.

The significant change in Barkhausen response following even small macroscopic plastic strain resulting from tensile loading above the yield point indicates that under zero applied stress, the specimen is in an "apparent" residual state of longitudinal compressive stress and transverse tensile stress. Other researchers, using different techniques, have obtained results for a variety of materials which generally tend to support these observations<sup>2</sup>. Thus, it can be concluded that after tensile deformation, a biaxial residual microstress system arises, at least within the near surface of the specimen. The dominating component is the compressive stress parallel to the direction of deformation. This "apparent" residual microstress system is dependent upon the amount of plastic deformation, and is an important factor in the Barkhausen noise characteristics of a plastically deformed steel specimen.

Results of orientation studies using the biaxial specimens are summarized in Fig. 13 which depicts the generalized relationship obtained between stress biaxility and probe orientation for four elastic strain states. These experiments were performed on cruciform specimens in the normalized state and because of a limited load capability in the horizontal direction were restricted to the elastic range. For any elastic strain state, the Barkhausen peak signal amplitude depends upon the angular orientation of the axis of magnetization (determined by the orientation of the pole pieces of the C-magnet) and the principal strain axes, which for the case under investigation, are fixed with respect to the longitudinal and transverse specimen axes. Here  $B^P$  is plotted in polar coordinates where  $B^P(\theta)$  is given in terms of the angular rotation from the longitudinal (L) axis. As anticipated, uniaxial tensile straining ( $\epsilon_L > 0$ ,  $\epsilon_T = 0$  and  $\epsilon_L = 0$ ,  $\epsilon_T > 0$ ) increases the signal amplitude for the direction of tensile strain, with a slight decrease for the orthogonal direction. Equal biaxial tensile straining ( $\epsilon_T = \epsilon_L = 0$  and  $\epsilon_L = \epsilon_T > 0$ ) increases  $B^P$  for all  $\theta$ . For other strain ratios, the curves obtained are similar.



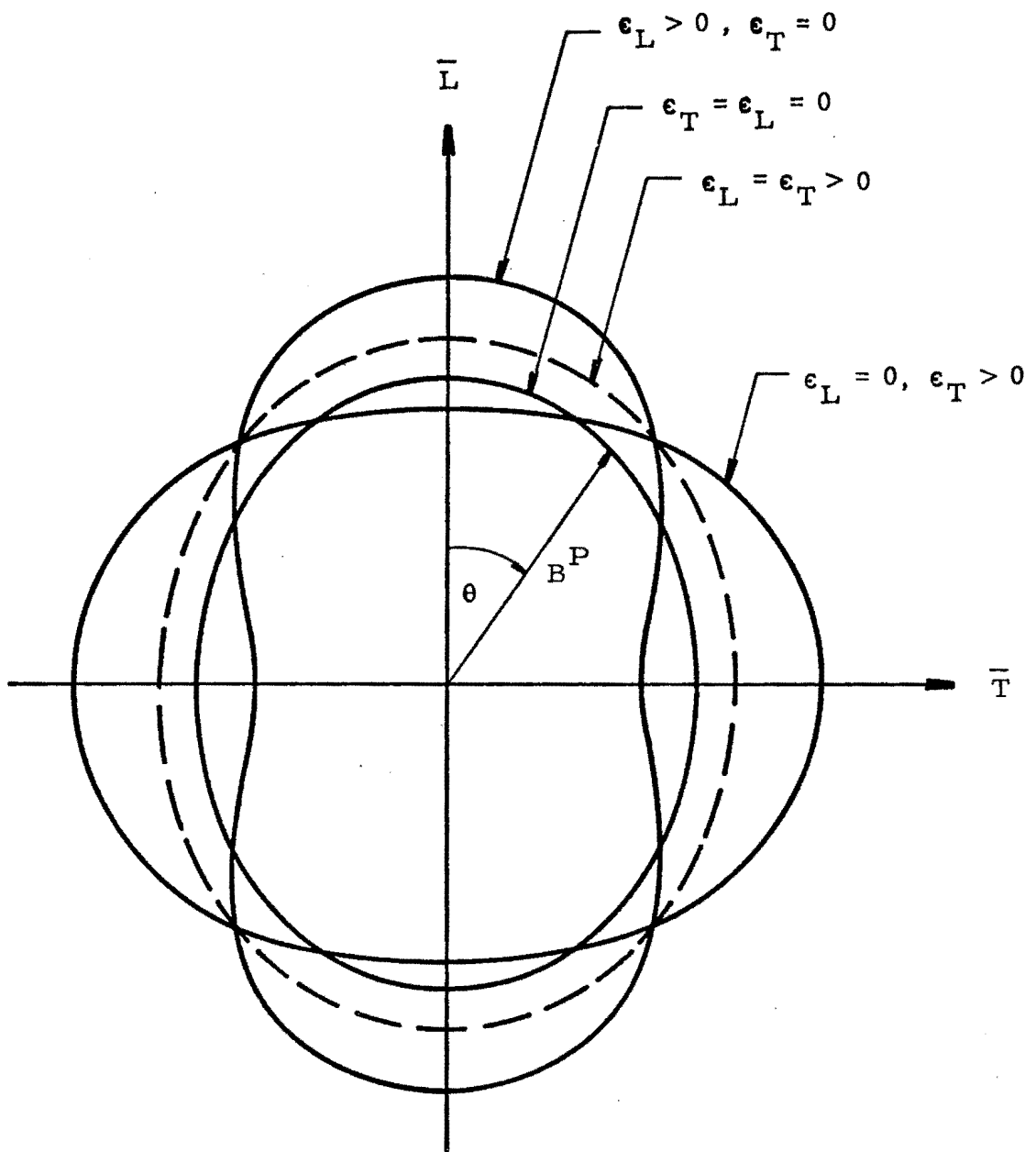


Fig. 13. Generalized Relationship Between Stress Biaxility and Barkhausen Probe Orientation

If the probe orientation is fixed in direction and the biaxial strain amplitudes are increased while holding the strain ratio constant, data such as that shown in Fig. 14 are obtained. The data for  $\bar{B}_L^P$  versus  $\epsilon_L$  are very much affected by the fact that the longitudinal direction (rolling direction) is the "easy" direction with respect to the magnetic Barkhausen effect. Thus the longitudinal Barkhausen signal is essentially independent of variations in the transverse strain component, except for the dominantly transverse strain ratios,  $\epsilon_L / \epsilon_T$  of 1/3 and 1/4. However, in the case of the transverse Barkhausen signal, as shown in Fig. 15 a plot of  $\bar{B}_T^P$  versus  $\epsilon_T$  exhibits a continuous variation in slope with strain ratio. The slope is positive for dominantly transverse strain ratios,  $\epsilon_T \gg \epsilon_L$ , and negative for dominantly longitudinal strain ratios,  $\epsilon_L \gg \epsilon_T$ .

To summarize, although the Barkhausen Noise Analysis method has been successfully applied to several specific problems of residual stress measurement<sup>3,4</sup>, the full potential of the method has not yet been realized because of the complex nature of the micro and macro magnetoelastic interactions which affect the observed signals. Residual stresses are produced in structures by the application of inhomogeneous mechanical or thermal stresses which produce localized yielding. Upon removal of the applied stresses, a residual inhomogeneous, self-equilibrating elastic stress field remains in the structure. The analog Barkhausen signal amplitude is found to be dependent upon both the magnitude and the ratio of the principal plastic strains during deformation, as well as the magnitude and ratio of the principal elastic strains remaining after unloading.

In addition, Barkhausen noise is affected by several factors in addition to stress; these include specimen metallurgical constitution; previous thermal and mechanical treatment; material anisotropy; and instrumental factors such as magnetization rate and probe-to-specimen lift-off. All of these have been studied to some extent<sup>5</sup>. What is needed now however is a systematic study to definitively delineate the influence of these various factors.

It is clear that additional basic research is needed to further develop the Barkhausen noise analysis method. Three approaches are suggested as being the principal avenues along which future exploratory and developmental effort should be directed: (1) well designed experiments controlling variables in order to separate and define the effects of the various factors which influence Barkhausen noise; (2) Barkhausen pulse counting and sorting experiments; and (3) characterization of the Barkhausen noise signal in appropriate stochastic terms.

The analog approach to analyzing the Barkhausen noise signal, as currently implemented in practice, is too limited in information content to allow automatic compensation for the influence of factors other than stress. Two candidate alternate approaches are (1) counting and sorting of individual pulses; and (2) utilization of the statistical nature of the Barkhausen noise signal. Although several investigations of the

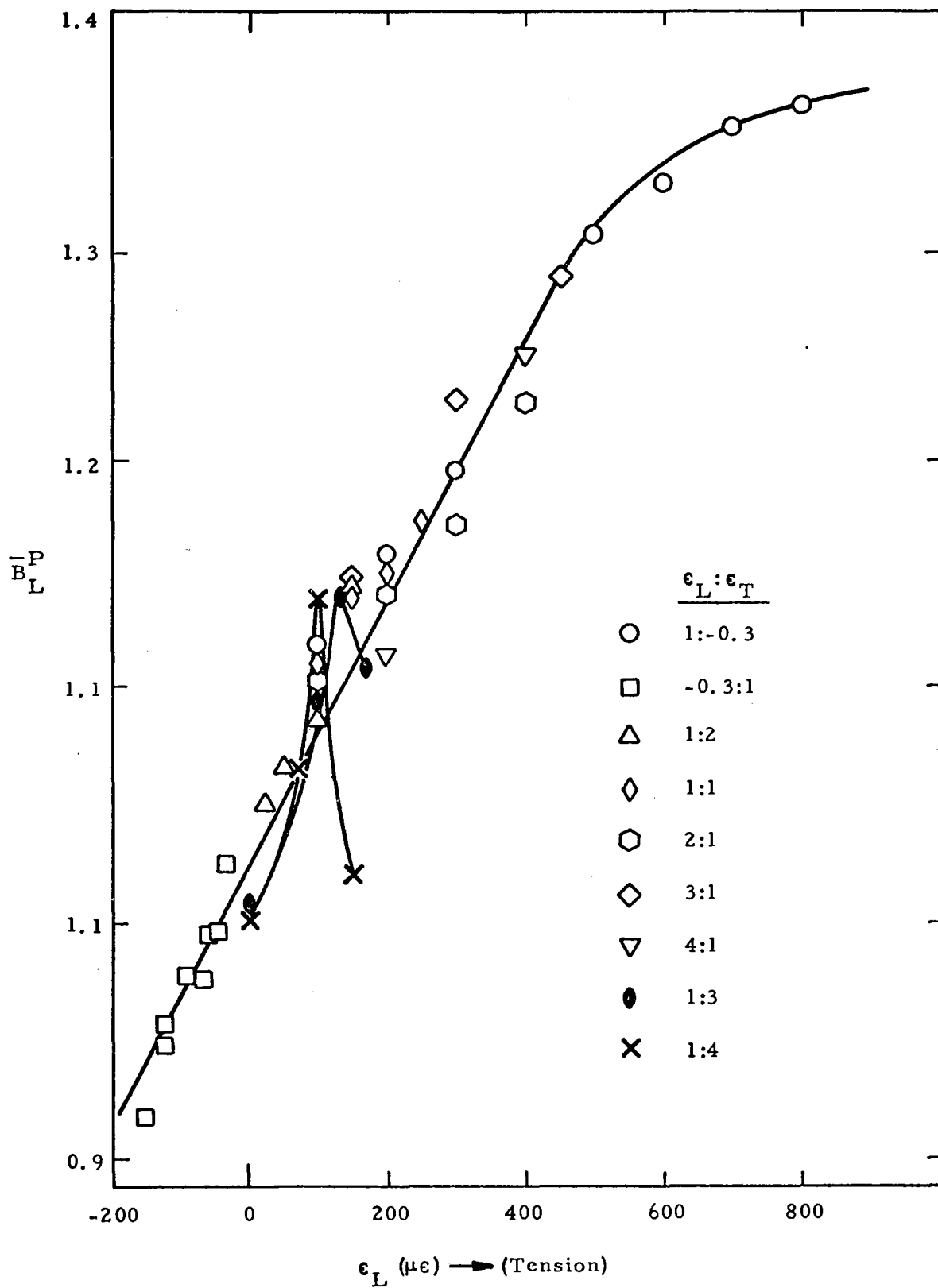


Fig. 14. Longitudinal Barkhausen Signal Versus Longitudinal Tensile Strain for Various Biaxial Stress States

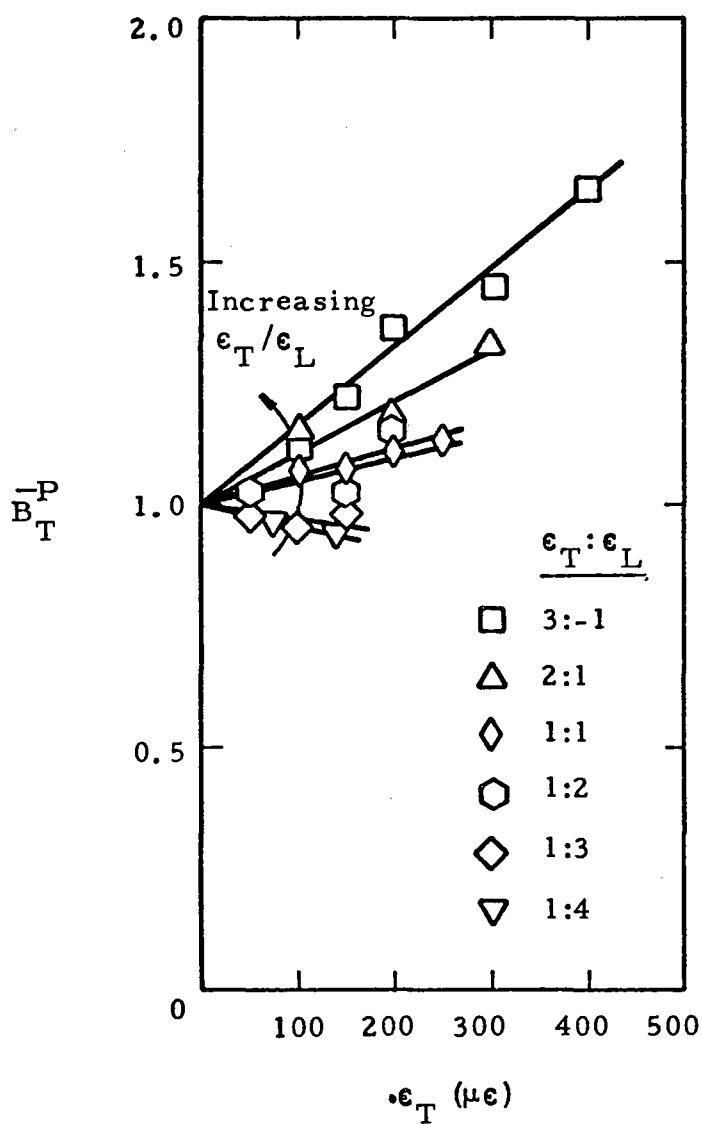


Fig. 15. Transverse Barkhausen Signal Versus Transverse Tensile Strain for Various Biaxial Stress States

power spectral density of Barkhausen noise have been reported<sup>4</sup>, a complete characterization of the underlying statistical nature of the Barkhausen noise has not yet been accomplished. It is anticipated that such studies will be useful in paving the way for broader realization of the potential of Barkhausen noise analysis in nondestructive evaluation.

#### References

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5. J. A. Birdwell and J. R. Barton, "Development and Application of Barkhausen Instrumentation Concepts for Measuring Stress in Ferromagnetic Steels," Final Report, Contract No. N00156-71-C-0362, Naval Air Engineering Center, Philadelphia, Pennsylvania, September 1971. Unpublished.

## DISCUSSION

- DR. WALKER (AFOSR, Washington): Are there any questions?
- DR. MEISTER (Battelle Columbus Lab.): How repeatable are these measurements? If you do one right after another are they repeatable?
- DR. MATZKANIN: Yes, they are repeatable within whatever scatter you'll see for a particular set of measurements. Generally speaking the data points in the Figures represent a number of measurements. They are quite repeatable.
- DR. WOLFGANG SACHSE (Cornell University): Do the results depend at all on the magnitude of the oscillating magnetic field you used?
- DR. MATZKANIN: Yes, right. This is one point that I didn't really get a chance to elaborate on; that is that there are a number of other factors which enter into the situation such as the magnetization rate, probe to specimen liftoff, the metallurgical constitution of the specimen, and thermal history of the specimen. So there are a number of influencing factors besides stress and one of the things that needs to be done is to design and conduct well-characterized experiments in which the influence of these various factors can be individually determined.
- DR. WALKER: Very good. Thank you very much.